Energy, Mines and Resources Canada
Energie, Mines et Ressources Canada

CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

RADIOACTIVITY CONDITIONS IN A NON-URANIUM UNDERGROUND MINE IN THE ABSENCE OF MINING OPERATIONS

J. BIGU, A. FRATTINI AND E. EDWARDSON

ELLIOT LAKE LABORATORY

MAY 1988

This document is an unedited interim report prepared primarily for ... and internal ... purposes. It does not ... final expression ... the opinion of the Canada ... Mines and Energy Technology (CANMET)

Ce document est un rapport ... rédigé ... de ... façon ... (CANMET)

43 pp

MINING RESEARCH LABORATORIES
DIVISION REPORT MRL 88-67 (TR)

MICROMEDIA

RADIOACTIVITY CONDITIONS IN A NON-URANIUM UNDERGROUND MINE IN THE ABSENCE OF MINING OPERATIONS

J. Bigu*, A. Frattini** and E. Edwardson**

ABSTRACT

Radiation and ventilation studies have been carried out at a non-uranium underground mine. This investigation was prompted because of reported radon gas and radon progeny concentrations as high, or higher, than concentration levels measured at conventional underground uranium mines. Measurements were conducted under normal operating ventilation conditions and when the ventilation system was partially and/or totally turned off. These measurements allowed the radioactivity build-up and clearance times to be calculated. These data are useful because they determine the radiation conditions worst case that would be encountered in the event of a ventilation system failure. Measurements of radon gas concentration in water samples leaves little doubt that the source of radon in the mine is water entering the mine site. It is calculated that the water influx is of about 0.08 m^3/s into a mine volume of approximately 1.5×10^4 m^3, therefore, leading to very wet underground working conditions.

Key words: Non-uranium mines; Radon gas; Radon progeny; Underground.

*Research Scientist, and Radiation/Respirable Dust/Ventilation Project Leader.
**Technologist, Elliot Lake Laboratory, CANMET, Energy, Mines and Resources Canada, Elliot Lake, Ontario.

CONCENTRATION DE LA RADIOACTIVITÉ DANS UNE MINE SOUTERRAINE NON MINÉRALISÉE EN URANIUM EN L'ABSENCE D'OPÉRATIONS MINIÈRES

J. Bigu*, A. Frattini** et E. Edwardson**

RÉSUMÉ

On a mené des études sur le rayonnement et la ventilation dans une mine souterraine non minéralisée en uranium. L'étude a été réalisée à la suite de rapports relatifs à des concentrations de radon et de descendants du radon, aussi élevées sinon plus, que les niveaux de rayonnement mesurés dans les mines classiques souterraines d'uranium. Les mesures ont été prises dans des conditions de ventilation habituelles quand le système de ventilation était soit partiellement ou complètement fermé. La méthode utilisée pour prendre les mesures permettait de calculer le temps d'accumulation et de dissipation des émanations radioactives. Ces données sont utiles car elles permettent de déterminer les pires conditions de concentrations d'émanations radioactives qui pourraient se produire advenant le cas d'une panne du système de ventilation. Les mesures des concentrations de radon dans les échantillons d'eau indiquent clairement que l'eau qui s'infiltre sur l'emplacement de la mine constitue la source première de radon dans une mine. D'après les calculs, l'entrée d'eau est d'environ 0,08 m^3/s par rapport au volume d'eau approximatif de $1,5 \times 10^4$ m^3 qui se trouve déjà dans la mine. Par conséquent, le milieu de travail dans les mines souterraines est très humide.

Mots-clé : mines non minéralisées en uranium; radon; descendants du radon; souterrain(ne).

*Chercheur scientifique, et Chef de projet, Rayonnement/Poussière inhalable/Ventilation,
**Technologue, Laboratoire d'Elliot Lake, CANMET, Énergie, Mines et Ressources Canada, Elliot Lake (Ontario)

CONTENTS

	Page
ABSTRACT	i
RESUME	ii
INTRODUCTION	1
EXPERIMENTAL PROCEDURE	2
EXPERIMENTAL RESULTS AND DISCUSSION	4
A. Zero Airflow Case	7
B. Non-Zero Airflow Case	9
C. Water Influx and Radon Gas in Mine Water	12
D. Radium (^{226}Ra) in Water Samples	13
E. Observations Regarding the Ventilation System	14
CONCLUSIONS AND RECOMMENDATIONS	15
ACKNOWLEDGEMENT	16
REFERENCES	16

TABLES

No.		
1.	Operation of the mine ventilation system	18
2.	Radon (thoron) progeny data and airflow conditions at location SS1	19
3.	Radon (thoron) progeny data and airflow conditions at location SS2	20
4.	Radon (thoron) progeny data and airflow conditions at location SS3	21
5.	Radon progeny data at several underground mine locations	22
6.	Radon gas concentration in air at several underground mine locations	23
7.	Radon gas concentration measured in water samples taken at several underground mine and surface locations	24
8.	Airflow rate conditions at sampling stations SS1, SS2 and SS3	25
9.	Underground meteorological data	26
10.	Geometric (physical) data and other miscellaneous data for the underground mine	27
11.	Range of values for radon progeny data measured at several mine locations	28
12.	Ratios of maximum to minimum values measured for different radiation variables	29

FIGURES

No.		Page
1.	Layout of underground site where measurements were carried out..	30
2.	Radon gas concentration and WL(Rn) versus time at location SS1..	31
3.	Radon gas concentration versus time at location SS1	32
4.	Radon gas concentration and WL(Rn) versus time at location SS1..	33
5.	Radon gas concentration and WL(Rn) versus time at location SS1..	34
6.	Radon progeny Working Level, WL(Rn), versus time at location SS2	35
7.	Radon progeny Working Level, WL(Rn), versus time for several locations	36
8.	Radon progeny concentrations (RPC) versus time for location SS1.	37
9.	Radon progeny concentrations, RPC, versus time for location SS2.	38
10.	Radon progeny concentration (RPC) ratios versus time for locations SS1 and SS2	39

INTRODUCTION

Low concentrations of uranium (^{238}U) and thorium (^{232}Th) minerals are distributed more or less uniformly throughout the crust of the earth. Uranium minerals are found in abundance in uranium mines. To some extent, thorium minerals are also found in relatively high amounts in some uranium mines.

Uranium-238 and ^{232}Th are the parents of two naturally occurring radioactive chains which give rise to radon gas (^{222}Rn) and thoron gas (^{220}Rn), respectively. These two radioactive gases once formed migrate through mine walls into mine atmospheres by diffusion and transport mechanisms. Radon and thoron decay in turn into their respective short-lived progenies, which once inhaled may pose an occupational health hazard.

Uranium mines are not alone in exhibiting appreciable concentrations of radon and its progeny. To a large extent, all underground mining environments show measurable concentrations of these radioisotopes. However, some non-uranium mines exhibit radon and radon progeny concentrations which are comparable to, if not higher than, uranium mines under average ventilation conditions. This is the case of some 'wet' mines where large amounts of groundwater and surface water enter the mine openings through the mine walls, shafts, drifts and the like. However, these anomalous cases are not only restricted to (non-uranium) wet mines.

The mechanism(s) whereby appreciable concentrations of radon and radon progeny are possible in some wet non-uranium mines is presumed to be as follows:

Water dissolves interstitial ^{222}Rn trapped in the pores of the rock formation or mineral ore which then enters mine openings. The radioactive gas is produced by the decay of $^{238}U/^{226}Ra$ minerals in the host rock or mineral ore. Alternatively, radon gas could be formed elsewhere outside the immediate

vicinity of the mine. In the latter case, radon gas from these outside locations is dissolved and carried by water into mine openings. The possibility of radium (^{226}Ra) being dissolved and carried by water into mine openings should not be discarded. However, this does not seem to be the most likely explanation for the case investigated here (see below), based on water sample analyses.

This report presents data regarding a comprehensive radiation and ventilation study carried out at a non-uranium underground mine. For simplicity, this study has been divided into two main parts, namely, a radiation/ventilation survey conducted in a period during which no mining operations were carried out, and another survey done about two months later when the mine was in full operation. The first phase of this project was aimed at determining build-up and clearance times of radioactive mine atmospheres when the ventilation system of the mine was turned off and on, respectively. The second phase of the project was conducted to assess the effect of mining operations on the radiation level of the mine atmosphere. The data in this report pertains to the first phase of this project.

EXPERIMENTAL PROCEDURE

Several sampling stations (SS) were chosen for monitoring purposes. These monitoring locations were labelled SS1, SS2, and SS3 for identification purposes (see Figure 1). Sampling location SS1 was located on the main ramp so as to monitor the return air exhausting from the mine. The exhaust site of the mine on the main ramp was essentially at ground level and was used by mine personnel, and vehicles, to access the working locations. Sampling station SS1 was situated about 60 m from the mine 'portal', i.e., the mine access and air exhaust site of the mine on the main ramp.

Sampling station SS2 was located on No. 1 level north, approximately

266 m from the portal (and ~206 m from SS1). Sampling station SS3 was situated in front of an electrical station on the main ramp approximately 180 m from the portal (and ~120 m from SS1).

A variety of radiation and meteorological measurements were carried out at the above locations and other locations. These include the following:

1. radon gas concentration, [^{222}Rn], in air;
2. radon progeny concentration in air, i.e., [^{218}Po], [^{214}Pb] and [^{214}Bi];
3. radon progeny Working Level, WL(Rn);
4. thoron progeny Working Level, WL(Tn);
5. radon gas concentration in water samples;
6. barometric pressure (P), air temperature (T), and relative humidity (RH) in the mine; and
7. ventilation characteristics, i.e., air flow rate, in the mine.

In addition, outdoor meteorological data collected by Environment Canada was used in this project. These data included measurements of P, T, RH, wind direction and wind velocity.

Data corresponding to items 1 to 3 were obtained by continuous monitoring techniques and grab-sampling methods only. Items 4 to 7 were obtained by grab-sampling methods only.

Continuous monitoring systems were located at sampling station SS1 for the measurement of [^{222}Rn] and WL(Rn), and at sampling station SS2 for the measurement of WL(Rn). Grab-sampling methods were also used at sampling stations SS1, SS2 and SS3 to determine [^{222}Rn] and WL(Rn).

Radon progeny Working Level measurements by continuous monitoring were conducted using Working Level continuous monitors, model α-PRISM, manufactured by alphaNUCLEAR (Toronto, Canada). Radon gas concentration measurements by continuous monitoring were carried out using radon gas continuous monitors, model AB-5/EL, manufactured by Pylon Electronic Development (Ottawa, Canada).

Grab-sampling measurements of WL(Rn) were done using α-particle scalers, model TM-372A, manufactured by Tri-Met (Winnipeg, Canada). Radon gas concentration in water samples was determined by the degassing method using a degassing unit, model RDU-200, manufactured by EDA (Toronto, Canada) in conjunction with ZnS(Ag) scintillation cells and a scaler, model RM-1003, manufactured by Pylon. Airborne radon gas concentration by grab-sampling was determined using ZnS(Ag) scintillation cells and scaler, model RM-1003.

Meteorological variables were measured by grab-sampling using conventional instrumentation. Air flow rate measurements were made by anemometry.

Measurements of [^{222}Rn], radon progeny concentration and WL(Rn) were carried out under normal ventilation conditions and when one or more ventilation and/or auxiliary fans were turned off. The operating conditions of the mine ventilation system are indicated in the graphs by encircled letters and vertical arrows pointing downward to indicate day and time of operation. A summary of the operation of the ventilation system is shown in Table 1. The mine ventilation system consisted of a main fan system made up of a large and a smaller fan (hereafter referred to as Fan 1 and Fan 2, respectively), and an auxiliary fan. The location of the fans is shown in Figure 1. The duration of the underground tests was one week (Nov./Dec. 1987).

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental data have been summarized in Tables 2 to 10, and Figures 2 to 10. Tables 2 to 7, and Figures 2 to 10 show radon and thoron progeny data. Tables 8 and 9 show air flow conditions and meteorological variables in the mine, respectively. Table 10 shows mine geometrical and physical data of interest. Tables 11 and 12 show miscellaneous radiation data.

Tables 2 to 5 show radon and thoron progeny data obtained by grab-sampling techniques using the Thomas-Tsivoglou method (1), and the Rock method (2), respectively (Tables 2 to 4). Tables 4 and 5 show radon progeny data obtained with an Instant Working Level Meter under the commercial name MIMIL (3,4). This instrument uses the Rolle method (5) for determining WL(Rn). The values by the MIMIL are given in $\mu J/m^3$ in accordance with the new definition of the Working Level in terms of the Potential Alpha Energy Concentration (PAEC), where 1 WL = 20.53 $\mu J/m^3$ according to the MIMIL instruction manual (Note: according to ICRP No. 32, 1 WL = 20.8 $\mu J/m^3$ (6)). For the benefit of the reader Tables 2 to 5 are given in the old and new units, i.e., WL(Rn) and $\mu J/m^3$, respectively. Similarly, radon progeny concentrations, e.g., [^{218}Po] are given in SI units, i.e., Bq/m^3, and in the more historical units, pCi/L, which appear in round brackets.

Figures 2 to 7 show WL(Rn) and [^{222}Rn] data by continuous monitoring mainly, whereas Figures 8 to 10 show radon progeny concentrations and radon progeny ratios by grab-sampling. Also shown in these Figures are the ventilation conditions, indicated by encircled upper case letters and vertical arrows pointing downward to the time axis. Table 1 shows the meaning of the different letters (symbols) used. Figure 4 shows WL(Rn) and [^{222}Rn] for 'normal' ventilation conditions. The same applies to Figure 2 until Dec. 1/87 at 13:30 when one of the ventilation fans was turned on. Figures 3, and 5 to 7 show the same variables under varying air flow conditions.

As the above data show, the values for the radiation variables observed in the mine varied markedly depending on airflow conditions and the location (sampling station) under consideration. The range of values measured are summarized in Table 11. It should be indicated that because of practical constraints a sample frequency had to be chosen compatible with other considerations. In our case samples were taken at 20 min intervals. Hence,

values higher than the maximum values shown in Table 11 are possible. Furthermore, airflow conditions when all the fans were off varied with each location depending on natural ventilation conditions prevailing at the time. These natural ventilation conditions depended partly on outdoor meteorological conditions, particularly at SS1.

The above observations apply to grab-sampling data. The same considerations, however, apply to data obtained by continuous monitoring systems except that in this case extra complicating factors enter into play, namely:

a) Because of the integrating nature of the sampling techniques used in some continuous monitoring systems, there is a time lag between the recording of an event and the actual occurrence of this event. For radon progeny the time delay (lag) is of about 1 hour;

b) Under rapid dynamic situations, important radiation information features may be 'missed' by some continuous monitoring systems if the sampling interval chosen is significantly longer than the time interval during which a given event occurs.

As expected, a pronounced difference in radiation conditions in the mine air was observed when the ventilation fan(s) were turned off. All radiation variables such as WL(Rn), $[^{222}Rn]$, radon progeny concentrations, e.g., $[^{218}Po]$, and radon progeny disequilibrium ratios increased rapidly. The ratios of maximum to minimum values for different radiation variables are given in Table 12. The F-value given in Tables 11 and 12 is defined by the relationship: $F = (WL(Rn)/[^{222}Rn]] \times 10^2$ where $[^{222}Rn]$ is given in pCi/L. The F-factor as well as the radon progeny disequilibrium ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$ are a measure of ventilation conditions and plate-out of radon progeny on mine walls.

The high values calculated for $F(\geq 0.75)$ and the very high values for

the radon progeny disequilibrium ratios (0.90-0.99) indicate that near equilibrium conditions were reached in the mine between radon gas and its progeny, and between the different members of the progeny series, when the ventilation fans were turned off. The high values for the above variables are indicative of extremely long mine air residence times and low selective plate-out of radon progeny on mine walls, and other large surfaces. (It should be noted that the maximum theoretical value for F and the radon progeny disequilibrium ratios is 1.)

Figures 3, and 5 to 7 illustrate a feature of great practical interest, namely the build-up and removal of radioactivity in the mine when the ventilation fans are turned off and on, respectively.

The above Figures show that, as expected, WL(Rn) and [^{222}Rn] increase after the ventilation fans are turned off. However, when normal airflow conditions are re-established, WL(Rn) and [^{222}Rn] at SS1 do not decrease immediately after ventilation conditions are back to 'normal' again, but they increase markedly, peaking at a certain value, to decrease rapidly thereafter until constant, steady-state levels are attained (see Figures 3, 5 and 7). For SS2 and SS3, however, this effect is far less pronounced as Figures 6 and 7 show. The reasons for this different behaviour will be discussed below.

The build-up and removal of radioactivity by ventilation can be divided into two parts, namely:

a) zero airflow by forced (mechanical) ventilation, i.e., Q=0. The only airflow is by natural ventilation: and

b) non-zero airflow, i.e., Q>0.

A. ZERO AIRFLOW CASE

In the situation depicted in item a), the radiation level in the mine will increase continuously until a maximum, steady-state value is reached.

This value may be modulated by natural ventilation conditions which, in turn, are affected by external meteorological conditions.

The rate of growth (build-up) of radioactivity in the mine, and the time taken for this radioactivity to reach an equilibrium (steady-state) condition depends on the half-life of the radioisotope under consideration (7). The maximum value for the radioactivity is a function of the rate of entry and release of radon gas in the mine environment. It should be noted that the term 'rate of release' refers to the case where radon gas is carried into the mine environment by a medium other than air, e.g., water in our case. The differences observed in the maximum value attained by the radiation level and the time taken to reach this maximum at different locations in the mine are attributed to:

i) local natural ventilation conditions; and

ii) non-uniform distribution and strength of the radon gas sources at different locations of the mine.

A point in case regarding items i) and ii) is shown by comparing Figures 3 and 5 with Figure 6, and by examining Figure 7. The data in these Figures clearly show that the radiation level build-up time for WL(Rn) and/or [^{222}Rn], and the maximum radiation level attained is much larger for sampling station SS2 than for sampling station SS1. This can be explained easily by noticing the following:

1. Strong natural ventilation conditions prevail at SS1 (60 m from the portal), caused by temperature and pressure differentials between SS1 and outdoors, which are absent in SS2; and
2. Large radon gas contribution in SS2 from high water influx into this area. (As will be illustrated below, radon gas dissolved in ground and surface water entering the mine is the major and probably only source of radon. Radon gas dissolved in water is released into the mine atmosphere

by friction, collision, transport and interphase exchange mechanisms.)

Furthermore, Figures 3, and 5 to 7 for Q=0 show that the build-up time for SS2 was ~12 h (B→C) and >15 h (D→E). For SS1, however, the build-up time was less defined because of moderate to strong (local) natural ventilation conditions, which changed often and rapidly. For example, the build-up time was ~6 h for the period A→B (Figure 2), but was far less defined for B→C (Figures 3 and 7), and undefined for D→E. In conclusion, the effect of turning off the ventilation fans was far less pronounced at sampling station SS1 than at sampling stations SS2 and SS3.

B. NON-ZERO AIRFLOW CASE

The dynamic situation for the case Q>0 (i.e., forced mechanical ventilation) is somewhat more complex than the case investigated above, i.e., Q=0.

As pointed out previously, radiation levels (WL(Rn) and [^{222}Rn]) at SS1 increased markedly at first, shortly after turning the ventilation fan(s) on, until a maximum value was attained to be followed by a rapid decrease until a constant, steady-state value was reached (see Figurs 3, 5 and 7).

This behaviour cannot be explained by assuming uniform mine air mixing, and hence a constant radiation level throughout the volume of the mine. If this were the case, an increase in airflow from Q=0 would certainly not affect the radiation levels observed at SS1 for some time: only after a period of time would the radiation levels decrease as air dilution mechanisms become important. Hence, no maximum (peak) would be observed, only a continuous decrease to a minimum value.

The observed effect could be explained, however, by the presence of [^{222}Rn] and WL(Rn) negative gradients between SS1 and other locations in the mine, particularly locations with large water influx rates (and hence high

[^{222}Rn]) and poor natural ventilation conditions. Locations that meet these requirements are abundant in the mine (see Tables 6. 7 and other data). Assuming plug flow. for the sake of simplicity. it is not difficult to visualize that when the ventilation fans are turned on. mine air is displaced from the volume of the mine close to the fresh ventilation air discharge and travels along the mine volume to the exhaust site (portal). Hence. a transient (maximum) radiation level should be expected followed by a decay because of air dilution.

Because stations SS2 nd SS3 are far from the portal where radiation levels are higher than at SS1. radiation concentration gradients between SS2 and SS3 and other mine locations further removed from the portal are less than for SS1. Hence. the transient effects discussed above should be significantly reduced for these two locations. This is in fact what is experimentally observed (see Figures 6 and 7).

Chronologically speaking. transient effects appear first at location SS3. then at SS2. and finally at SS1. This sequence can be easily understood from the mine ventilation layout (see Figure 1). The time elapsed between turning on the fans and the occurrence of a transient (e.g.. maximum) at a given location is a measure of the mine air transit time. or air residence time. The time until the steady-state. constant value is reached is a measure of the mine air clearance time. These times will. of course. vary with the location of the sampling station.

The mine air transit time and clearance time calculated from Figures 3 and 5 to 7 may give different results depending on whether use is made of continuous monitoring data or grab-sampling data. However. this difference is more apparent than real. Naturally. the results should be the same. The difficulty arises from the interpretation of the data. In order to clarify this point. the reader should be aware of the following:

a) as previously indicated. data recorded by continuous monitoring devices of the time integrating type (e.g.. alphaPRISM. and to some extent the AB-5/EL) exhibit a time lag with respect to the actual occurrence of an event of ~1 hour.

b) continuous radiation monitoring devices tend to smooth out rapidly changing radiation conditions. If the sampling time is of the same order or longer than the period of the radiation event. the device may show a largely reduced response or miss the event altogether:

c) a sudden and very steep change (decrease) in radiation conditions will cause the continuous monitoring device to respond with a rather long radioactive decay tail. This is due to the decay of the radon progeny in the sampling filter. This situation is analogous to sampling air at a given flow rate and then turning the sampling pump off. The activity in the filter will decay according to well known laws. For radon progeny it will take 3-4 h for the activity to decay completely.

d) there is a time lag between the appearance of radon gas and its progeny. This is to be expected. and well understood on theoretical grounds as ^{218}Po is formed by the decay of ^{222}Rn (half-life ~3.82 d). and so on.

Items a) to c) are responsible for a substantial broadening and time shifting of the radiation response of the instrument with respect to the time profile of the actual radiation event. The Figures in the text clearly show this.

Other differences between profiles by grab-sampling and continuous monitoring can be ascribed partly to the particular sampling frequency chosen.

Examination of the data presented in the Figures shows that the approximate mine air clearance times are. 2.25 h for SS1. 2.5 h for SS2. and 2.7 h for SS3. i.e.. in excess of 2 h in each case. These figures are subject to some uncertainty because of items a) to d).

C. WATER INFLUX AND RADON GAS IN MINE WATER

Relatively high concentrations of radon gas (Table 6) have been measured in air in this non-uranium underground mine. Because this is a non-uranium mine. the question arises as to where the radon gas comes from?

Because of the usually very wet conditions in the mine and the highly fractured nature of the surface of the mine walls. installation and measurement of radon flux by fluxmeter cans was extremely difficult. and hence. not attempted.

Radon flux measurements at dry locations of the mine using fluxmeter cans would identify the presence of radon gas in interstitial pores in the rock formation. The radon 'trapped' in the pores emanates into open spaces by diffusion (concentration gradients) and convective (transport) processes. Because of the rather limited diffusion length of radon gas in most materials. i.e.. <2-3 m (8.9). the measurement of an appreciable radon gas flux would indicate the presence of ^{238}U and ^{226}Ra in the immediate vicinity of the mine. i.e.. mine walls. ceiling and floors.

Direct radon gas flux measurements failing. the second choice was to determine the presence of ^{222}Rn and its parents (^{238}U and ^{226}Ra) in waste rock and ore by emanation studies. Measurements of this kind will be reported elsewhere when completed.

A strong suspicion. confirmed by direct measurement. was the presence of radon gas dissolved in water entering the mine. (This is supported by previous studies by other workers in adjacent mines.)

Water samples were taken from a number of locations and degassed by conventional techniques. The gas was collected in scintillation cells and the α-particle activity was measured and followed for a period of time. The observed radioactive half-life of the gas confirmed the presence of radon in

water samples. Table 7 summarizes some of the results obtained. Radon gas concentrations in excess of 2.0×10^6 Bq/m^3 (~5.5×10^4 pCi/L) were obtained. At the surface water discharge point the activity concentration measured was ~3.1×10^5 Bq/m^3 (~8.4×10^3 pCi/L).

Assuming a water influx into the mine of about 5 m^3/min (10), a radon gas emanation coefficient in water of 0.5 (50%), and an average [^{222}Rn] in water of 3.8×10^5 Bq/m^3 (~1.0×10^4 pCi/L), a straightforward calculation shows that the rate of release of activity into the mine volume (~1.5×10^4 m^3) is:

$$5 \times 3.8 \times 10^5 \times 0.5 = 9.5 \times 10^5 \text{ Bq/min } (\sim 2.6 \times 10^7 \text{ pCi/min}).$$

The above calculation is a crude one because of the large uncertainty in the values for the average radon gas concentration in water, the radon gas emanation coefficient, and geometric distribution of water sources with different radon gas concentrations, and other variables not discussed here.

The influence and interplay of the above variables, and the modelling of the mine, assuming water as the major carrier of radon gas into the mine, is beyond the scope of this report. This topic will be discussed at length in a separate forthcoming report.

It should be noted that if radon gas dissolved in water is the main source of radon entering the mine at different locations, the source of radon could be, in principle, far removed from the mine site. This contention, however, cannot be verified without further experimentation and hydrological information.

D. RADIUM (^{226}Ra) IN WATER SAMPLES

It has been assumed above that the radon gas measured in water was actually radon gas dissolved in the samples. However, the possibility of radium (^{226}Ra) dissolved in water as the origin of radon gas should also be

considered. In order to do this. water samples were completely degassed. and stored in leak-free glass containers. After one month. water samples were degassed again and the gas collected in scintillation cells was measured. The result of these tests indicated almost negligible amounts of ^{226}Ra in water. Hence. it may be concluded that the radon gas measured in water was indeed radon gas dissolved in the water samples.

E. OBSERVATIONS REGARDING THE VENTILATION SYSTEM

Careful inspection of the ventilation tubing showed numerous holes. tears and large openings (splits) with substantial loss of ventilation air. Furthermore. ventilation tubing of a smaller diameter than desirable was used in a side branch. thereby contributing to energy losses by friction.

Another important observation made was that water dripping from the mine ceiling collected in relatively large quantities in the ventilation tubing. Several locations where this occurred were identified. The weight of the water caused deformation and bending of tubing leading to the formation of water 'ponds' at the bottom of the ventilation tubing. Because radon gas is dissolved in water and the surface of the water ponds in the tubing was subjected to large airflows and air linear velocities. degassing of radon was greatly encouraged under these conditions. This would explain the higher than expected WL(Rn) (>0.08) in mine areas near the fresh ventilation air discharge where. in principle. negligible radiation levels should be observed.

From the above discussion. it is recommended that for optimum operating conditions the ventilation tubing should be inspected on a daily basis and repairs made when leakages are identified. This practice will in turn improve airflow in needed areas. reduce radiation levels and minimize ventilation costs.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusions that can be drawn from this study are listed below.

1. Elevated radon gas and radon progeny concentrations were measured in this wet non-uranium mine. The radiation levels observed under normal ventilation conditions (no mining operations) were as high or higher than those measured in conventional underground uranium mines.
2. Radiation levels when the mine ventilation system was turned off were considerably higher than radiation levels under normal ventilation conditions. In some cases, radiation levels increased by more than two orders of magnitude over their usual level.
3. The source of radiation in this non-uranium mine has been traced to water entering the mine site through walls and other large mine surfaces. Radon gas concentration in water samples in excess of 2×10^6 Bq/m^3 ($\sim 5.5 \times 10^4$ pCi/L) were measured. Taking into account that the water influx in the mine is about 5 m^3/min. and the high radon gas concentration levels in water indicated above, it is possible to calculate (theoretically) the radiation level in the mine from ventilation conditions and water source distribution considerations.
4. No appreciable radium (^{226}Ra) was found in water samples.
5. When the ventilation fans were turned off, near equilibrium conditions in the mine were attained given by the high values for the F-factor, and the radon progeny disequilibrium ratios. These high values are also indicative of very long mine air residence times, as expected.
6. Radioactivity build-up time and clearance time depended on mine location, and natural and forced ventilation conditions. These data are important to assess radioactivity dose exposure in the event of a failure in the

operation of the ventilation system.

Ventilation conditions should at least be maintained at the present level or improved. Accumulation of water in the ventilation tubing should be avoided because this is a source of radon.

The ventilation tubing should be inspected on a regular basis and repaired if necessary in order to improve ventilation conditions in the mine.

The modelling of the mine will be deferred to a forthcoming report. and only after analysis of data collected during a similar study when the mine was fully operative. i.e.. mining operations were carried out. is completed.

ACKNOWLEDGEMENT

The authors are grateful to the mine personnel for their kind and helpful response to this study.

REFERENCES

1. Thomas. J.W.. "Measurement of radon daughters in air": Health Physics. vol. 23. pp 783-789. 1972.

2. Rock. R.L.. "Sampling mine atmospheres for potential α-energy due to presence of radon (thoron) daughters": Information Report IR 1015. U.S. Bureau of Mines (Dept. of the Interior). 1975.

3. Bigu. J.. "A technical evaluation of a radon progeny Instant Working Level Meter in an underground uranium mine": Division Report MRL 87-110(TR). CANMET. Energy, Mines and Resources Canada: August 1987.

4. Bigu. J.. "Laboratory evaluation of the MIMIL. a radon progeny Instant Working Level Meter": Division Report MRL 88-27(TR). CANMET. Energy. Mines and Resources Canada: April 1988.

5. Rolle, R.. "Improved radon daughter monitoring procedures": Am. Ind. Hyg. Assoc. J.. vol 30. pp 153-160. 1969. (See also Health Physics. vol 22. pp

233-238. 1972.)

6. ICRP Publication 32. "Limits for inhalation of radon daughters by workers". Annals of the International Commission on Radiological Protection. vol 6. No. 1. 1981. Pergamon Press. Oxford. New York.

7. Bigu. J.. "Theoretical models for determining ^{222}Rn and ^{220}Rn progeny levels in Canadian underground uranium mines - a comparison with experimental data": Health Physics. vol 48. No. 4. pp 371-399. 1985.

8. Schroeder. G.L.. "Diffusion of radon in several naturally occurring soil types": J. Geophys. Research. vol 70. pp 471-474. 1965.

9. Tanner. A.B.. "Radon migration in the ground: a review": in The Natural Radiation Environment. (Chicago. IL. the University Press) pp 161-190. 1964.

10. Private communication by mine personnel and other officials. 1988.

Table 1 - Operation of the mine ventilation system

Date	Time	Fan 1	Fan 2	Auxiliary Fan	Symbol
Dec. 1/87	13:30	OFF	ON	ON	A*
Dec. 1/87	21:52	OFF	OFF	ON	B
Dec. 2/87	10:00	ON	ON	ON	C
Dec. 2/87	17:32	OFF	OFF	OFF	D
Dec. 3/87	09:06	ON	ON	ON	E

*Prior to Dec. 1/87 at 13:30, fans 1 and 2 , and the auxiliary fan were on at all times.

Table 2 - Radon (thoron) progeny data and airflow conditions at location SS1. Radiation data obtained by the Thomas-Tsivoglou method (1), and the Rock method (2).

Date	Time	$[^{218}Po]$ Bq/m^3 (pCi/L)	$[^{214}Pb]$ Bq/m^3 (pCi/L)	$[^{214}Bi]$ Bq/m^3 (pCi/L)	Q* m^3/3	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	WL(Rn)	PAEC µJ/m^3	WL(Tn)	$\frac{WL(Tn)}{WL(Rn)}$	Remarks
Nov. 30/87	14:02	1924 (52.0)	788 (21.3)	392 (10.6)		0.41	0.20	0.20	4.16	NM[a]		
	14:47	1724 (46.6)	714 (19.3)	377 (10.2)		0.41	0.22	0.18	3.74	NM		
	15:00				17.2							
	15:11							0.21	4.40			
	15:32	1647 (44.5)	692 (18.7)	500 (13.5)		0.42	0.30	0.19	3.95	NM		
	16:12	2172 (58.7)	821 (22.2)	326 (8.8)		0.38	0.15	0.21	4.37	0.006	0.030	
Dec. 1/87	09:15				14.8			0.21	4.37			
	10:47	1935 (52.3)	788 (21.3)	285 (7.7)		0.41	0.15	0.19	3.95			
	11:32	1865 (50.4)	725 (19.6)	303 (8.2)		0.39	0.16	0.18	3.74			
	13:32	1994 (53.9)	629 (17.0)	440 (11.9)		0.32	0.22	0.19	3.95			at 13:30 fan 1 off
	14:35				3.8							
	14:52	3704 (100.1)	1550 (41.9)	855 (23.1)		0.42	0.23	0.40	8.32	NM		
	15:32	2401 (64.9)	1628 (44.0)	862 (23.3)		0.68	0.36	0.38	7.90	0.005	0.014	
	16:27	4695 (126.9)	1939 (52.4)	1154 (31.2)		0.41	0.25	0.51	10.61	0.006	0.013	at 21:52 fan 1 & 2 off
Dec. 2/87	08:39	2967 (80.2)	2260 (61.1)	1769 (47.8)		0.76	0.60	0.57	11.86			
	10:37	11943 (322.8)	9946 (268.8)	9228 (249.4)		0.83	0.77	2.63	54.70	0.007	0.003	at 10:00 fan 1 & 2 on
	11:05				16.8							
	11:17	3063 (82.8)	1976 (53.4)	1865 (50.4)		0.64	0.61	0.54	11.23			
	11:52	2900 (78.4)	1203 (32.5)	570 (15.4)		0.41	0.20	0.30	6.24			
	13:50				15.3							
	14:02	2005 (54.2)	677 (18.3)	252 (6.8)		0.34	0.13	0.17	3.54			
	15:57	2102 (56.8)	740 (20.0)	204 (5.5)		0.35	0.10	0.18	3.74			at 17:32 fan 1 & 2 off; auxiliary fan off.
Dec. 3/87	08:37	2009 (54.3)	1672 (45.2)	1462 (39.5)		0.83	0.73	0.43	8.94			
	08:57							0.46	9.57	0.006	0.014	
	09:17							12.66	263.33	0.006	0.001	at 09:06 fan 1 & 2 on;
	09:32	21730 (587.3)	21560 (582.7)	21427 (579.1)		0.99	0.99	5.72	118.98			auxiliary fan on.
	09:47							3.20	66.56			
	10:02							1.55	32.24			
	10:17							1.03	21.42			
	10:32							0.58	12.06			
	10:47							0.42	8.74			
	11:02							0.35	7.28			
	11:22							0.26	5.41			
	11:52							0.20	4.16			
	14:00				13.7							

Note: * Q stands for airflow rate. [a] NM stands for not measurable.

Table 3 - Radon (thoron) progeny data and airflow conditions at location SS2. Radiation data obtained by the Thomas-Tsivoglou method (1) and the Rock method (2).

Date	Time	$[^{218}Po]$ Bq/m^3 (pCi/L)	$[^{214}Pb]$ Bq/m^3 (pCi/L)	$[^{214}Bi]$ Bq/m^3 (pCi/L)	Q* m^3/s	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	WL(Rn)	PAEC µJ/m^3	WL(Tn)	$\frac{WL(Tn)}{WL(Rn)}$	Remarks
Nov. 30/87	14:02	6175 (166.9)	2605 (70.4)	1357 (36.7)		0.42	0.22	0.67	13.94	0.013	0.019	
	14:47	6031 (163.0)	2490 (67.3)	1450 (39.2)		0.41	0.24	0.66	13.73	0.006	0.009	
	15:32	7348 (198.6)	2953 (79.8)	1043 (28.2)	1.5	0.40	0.14	0.72	14.98	0.022	0.031	
	15:38							0.61	12.69	0.031	0.051	
	16:12	6327 (171.0)	2834 (76.6)	1535 (41.5)		0.45	0.24	0.72	14.98			
Dec. 1/87	09:32				3.5			0.28	5.78			
	09:47	3855 (104.2)	1394 (37.7)	751 (20.3)		0.36	0.19	0.37	7.70	NM[a]		Repairs made to vent. tubing in level 1 north
	09:49							0.33	6.78			
	10:47	3644 (98.5)	1232 (33.3)	329 (8.9)		0.33	0.09	0.30	6.24	NM		
	11:37				2.9			0.30	6.24	NM		
	13:32	3851 (104.1)	1043 (28.2)	444 (12.0)		0.27	0.12	0.30	6.24			13:30 fan 1 off.
	14:08				3.7			0.38	7.90			
	14:52	4484 (121.2)	1835 (49.6)	892 (24.1)		0.41	0.20	0.47	9.78			
	15:32	5131 (138.7)	1939 (52.4)	984 (26.6)		0.38	0.18	0.51	10.61	0.004	0.008	
	16:28	6519 (176.2)	2305 (62.3)	1450 (39.2)		0.35	0.22	0.64	13.31	NM		21:52 fan 1 & 2 off.
Dec. 2/87	08:39	27251 (736.5)	19432 (525.2)	16472 (445.2)		0.71	0.60	5.09	105.87	0.015	0.003	
	08:50				2.3							
	10:37	17586 (475.3)	14234 (384.7)	12998 (351.3)		0.80	0.74	3.75	78.0	0.007	0.002	10:00 fan 1 & 2 on.
	11:17	5813 (157.11)	2875 (77.7)	2253 (60.9)		0.49	0.39	0.78	16.22			
	11:52	4362 (117.9)	1635 (44.2)	903 (24.4)		0.37	0.21	0.44	9.15			
	14:02	3867 (104.5)	1125 (30.4)	440 (11.9)		0.29	0.11	0.31	6.45			
	15:57	3441 (93.0)	1021 (27.6)	459 (12.4)		0.30	0.13	0.28	5.82			17:32 fan 1 & 2 off, auxiliary fan off.
Dec. 3/87	08:37	92981 (2513)	83250 (2250)	73926 (1998)		0.90	0.80	21.46	446.36	0.017	0.0008	
	08:57							23.39	486.51	0.018	0.0008	
	09:17							18.22	378.98	0.013	0.0007	09:06 fan 1 & 2 on; auxiliary fan on.
	09:32							10.62	221.73			
	09:47							4.43	92.1			
	10:02							2.24	46.6			
	10:17							1.35	28.08			
	10:32							0.82	17.06			
	10:47	4825 (130.4)	2005 (54.2)	1510 (40.8)		0.42	0.31	0.61	12.69			
	11:12							0.43	8.94			
	11:42							0.33	6.86			
	14:40				5.4							Measurement taken with Kurtz model 480 on low setting.

Note: [a] NM stands for not measurable. * Q stands for airflow rate.

Table 4 - Radon (thoron) progeny data and airflow conditions at location SS3. Radiation data obtained by the Thomas-Tsivoglou method (1) and Instant Working Level Meter under the commercial name MIMIL (4).

Date	Time	$[^{218}Po]$ Bq/m^3 (pCi/L)	$[^{214}Pb]$ Bq/m^3 (pCi/L)	$[^{214}Bi]$ Bq/m^3 (pCi/L)	Q m^3/s	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	WL(Rn)	PAEC $\mu J/m^3$	WL(Tn)	$\frac{WL(Tn)}{WL(Rn)}$	Remarks
Nov. 30/87	15:55							0.13	2.81			
Dec. 1/87	10:29							0.11	2.21			13:30 fan 1 off
	14:18				4.2							21:52 fan 1 & 2 off
Dec. 2/87	09:35	47286 (1278)	42735 (1155)	39886 (1078)		0.90	0.84	11.2	232.96	0.026	0.002	
	10:25							2.61	54.32			10:00 fan 1 & 2 on
	10:40							1.12	23.24			
	10:55				12.1			0.61	12.65			
	11:27							0.28	5.82			
	13:53							0.13	2.70			
	15:44							0.12	2.50			
	16:07							0.11	2.29			17:32 fan 1 & 2 off; auxiliary fan off.
Dec. 3/88	08:43							4.90	101.9			
	09:00							6.46	134.3			
	09:05:52											09:06 fan 1 & 2 on;
	09:15							10.90	226.8			auxiliary fan on.
	09:30							3.07	63.08			
	09:45							1.53	31.81			
	10:00							0.85	17.76			
	10:15							0.44	9.25			
	10:30							0.31	6.40			
	11:05							0.18	3.68			
	11:40							0.15	3.23			
	15:15				11.8							

Note: Q stands for airflow rate.

Table 5 - Radon progeny data at several underground mine locations. Data obtained with an Instant Working Level Meter under the commercial name MIMIL (4).

Date	Time	Mine Location	WL(Rn)	PAEC $\mu J/m^3$
Dec. 1/87	10:08	Level 1 north end of drift	0.14	2.99
Dec. 3/87	14:51	Level 1 north end of drift	0.11	2.28
Dec. 2/87	17:00	SP2*	0.37	7.76
Dec. 2/87	16:40	SP3	0.32	6.64
Dec. 2/87	15:57	SP4	0.49	10.1
Dec. 2/87	15:11	X-cut 2A	0.07	1.46
Dec. 2/87	15:37	X-cut 2A	0.06	1.32
Dec. 2/87	16:18	X-cut 2B	0.20	4.23
Dec. 2/87		Sub-Ramp	0.14	2.91

* Note: SP stands for sump pump.

Table 6 - Radon gas concentration in air at several underground mine locations. Data obtained by grab-sampling.

Date	Time	Location	[^{222}Rn] Bq/m^3 (pCi/L)
Nov. 30/87	14:00	SS1	2.775 (75)
Nov. 30/87	14:10	SS2	7.585 (205)
Dec. 1/87	10:49	SS1	2.886 (78)
Dec. 1/87	10:59	SS2	5.476 (148)
Dec. 1/87	16:28	SS2	7.992 (216)
Dec. 1/87	16:34	SS1	5.402 (146)
Dec. 2/87	09:03	SS1	4.218 (114)
Dec. 2/87	09:12	SS2	37.666 (1018)
Dec. 2/87	16:55	SP2	4.958 (134)
Dec. 2/87	16:33	SP3	10.989 (297)
Dec. 2/87	15:52	SP4	9.805 (265)
Dec. 2/87	15:31	X-cut 2A	851 (23)
Dec. 2/87	16:12	X-cut 2B	3.441 (93)
Dec. 3/87	14:44	End level 1 north	1.406 (38)

Note: SP stands for sump pump.

Table 7 - Radon gas concentration measured in water samples taken at several underground mine and surface locations (see Fig. 1)

Date	Location	[^{222}Rn] Bq/m^3 (pCi/L)	Remarks
Nov. 30/87	Level 2B	416.546 (11258)	Underground sample
Nov. 30/87	Level 1 north (SS2)	222.000 (6000)	" "
Dec. 1/87	SP1	3.996 (108)	" "
Dec. 1/87	SP2	211.825 (5725)	" "
Dec. 1/87	SP3	380.471 (10283)	" "
Dec. 1/87	SP4	263.921 (7133)	" "
Dec. 1/87	Sub-ramp 2B	552.040 (14920)	" "
Dec. 1/87	X-cut 2A	590.446 (15958)	" "
Dec. 3/87	End of level 1 north	2.015.279 (54467)	" "
Dec. 3/87	Tailings pond	2.775 (75)	Surface sample
Dec. 3/87	Surface discharge	312.021 (8433)	" "

Note: The values for the radon gas concentration, [^{222}Rn], in water samples given above represent lower limit estimates based on water samples degassed twice independently. Measurements show, however, that appreciable amounts of ^{222}Rn still remain in water samples after degassing the samples twice as recommended by the manufacturer of the instrumentation used in these measurements. It is concluded that the data of the above table underestimate the true values of [^{222}Rn] by $\gtrsim$10%.

Table 8 - Airflow rate conditions at sampling stations SS1, SS2 and SS3

Date	Time	Location	Q^1 (m^3/s)	Remarks
Nov. 30/87	15:00	SS1	17.2	
Dec. 1/87	09:25	"	14.8	
Dec. 1/87	14:35	"	3.8	Fan 1 OFF
Dec. 2/87	11:05	"	16.8	
Dec. 2/87	13:50	"	15.3	
Dec. 3/87	14:00	"	13.7	
Nov. 30/87	15:20	SS2	1.5	
Dec. 1/87	09:35	"	3.5	Holes in vent. tubing repaired
Dec. 1/87	11:40	"	2.9	
Dec. 1/87	13:45	"	3.7	
Dec. 2/87	08:50	"	2.3	
Dec. 3/87	14:40	"	5.4*	
Dec. 1/87	14:18	SS3	4.2	Fan 1 OFF
Dec. 2/87	10:52		12.1	
Dec. 3/87	15:15		11.8	

Note: [1] The symbol Q is used to indicate airflow rate.

* Measurement made with airflow meter model Kurtz 480 . The rest of the measurements were made with a vane anemometer.

Table 9 - Underground meteorological data (temperature (T), relative humidity (RH), and barometric pressure (P))

Date	Location	T (^{o}C)	RH (%)	P kPa
Nov. 30/87	SS1	6.8	89	99.8
Nov. 30/87	SS2	8.3	95	99.8
Dec. 1/87	SS1	9.5	85	98.8
Dec. 1/87	SS2	8.7	84	99.0
Dec. 2/87	SS1	8.6	80	97.3
Dec. 2/87	SS2	10.8	82	97.8
Dec. 2/87	SS3	7.9	90	-
Dec. 2/87	SS1	8.4	83	97.5
Dec. 2/87	SS2	9.2	84	97.8
Dec. 2/87	SS3	8.7	88	-
Dec. 2/87	SS1	8.2	90	97.4
Dec. 2/87	SP2	9.0	-	97.8
Dec. 2/87	SP3	9.0	-	97.8
Dec. 2/87	SP4	9.0	-	97.8
Dec. 2/87	X-cut 2A	9.0	-	97.8
Dec. 2/87	X-cut 2B	9.0	-	97.8
Dec. 2/87	end of level N*	8.0	-	97.4
Dec. 3/87	SS1	7.3	~99	97.2
Dec. 3/87	SS2	10.3	85	97.3
Dec. 3/87	SS3	9.2	86	97.5
Dec. 3/87	SS1	7.2	94	97.1
Dec. 3/87	SS2	7.7	94	97.5
Dec. 3/87	SS3	7.2	94	97.4
Dec. 3/87	SS1	7.4	94	97.1
Dec. 4/87	SS1	7.1	87	98.3
Dec. 4/87	SS2	8.0	89	98.4

Note: * N stands for north.

Table 10 - Geometric (physical) data and other miscellaneous data for the underground mine

Location		Distance
From	To	(m)
SS1	Portal	60
SS2	SS1	206
SS2	Portal	266
SS3	SS1	120
SS3	Portal	180
End of level 1 north	Portal	476
End of X-cut 2A	Junction main ramp	275
End of X-cut 2B	X-cut 2A/subramp	190
End of main drift	Portal	950

The following cross-sections (X-sections) were measured:

X-section for SS1 : 19.0 m^2

X-section for SS2 : 23.3 m^2

X-section for SS3 : 19.7 m^2

Average X-section for the mine : ~16.0 m^2

Volume of the mine : ~1.52 x 10^4 m^3

Ventilation rate with all fans operating : ~16 m^3/s

Table 11 - Range of values for radon progeny data measured at several mine locations.

Location	$[^{218}Po]$ (Bq/m^3)	$[^{214}Pb]$ (Bq/m^3)	$[^{214}Bi]$ (Bq/m^3)	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	WL(Rn)	$[^{222}Rn]$ Bq/m^3	F
SS1	1647-21730	629-21560	204-21427	0.32-0.99	0.10-0.99	0.17-12.66	$<1.0x10^3$-$2.5x10^4$*	0.21-($\geq$)0.75
SS2	3644-92981	1043-83250	329-73926	0.27-0.90	0.09-0.8	0.28-23.39	5,476-37,666	-
SS3	-	-	-	-	-	0.11-11.2		-

Notes: To convert Bq/m^3 to pCi/L divide above values by 37.

To convert WL(Rn) to $\mu J/m^3$ multiply by 20.53.

* Value obtained by a continuous monitoring system (model AB-5/EL by Pylon Electronic Development).

Table 12 - Ratios of maximum to minimum values measured for different radiation variables. Maximum and minimum values were obtained with fan(s) off and fans on, respectively.

Location	$[^{218}Po]$ (Bq/m^3)	$[^{214}Pb]$ (Bq/m^3)	$[^{214}Bi]$ (Bq/m^3)	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	WL(Rn)	$[^{222}Rn]$ (Bq/m^3)	F-value**
SS1	13.2	34.3	105.0	3.09	9.9	74.5	25.0*	$\tilde{>}$3.6
SS2	25.5	79.8	224.7	3.33	8.9	83.5	6.9[1]	-
SS3	-	-	-	-	-	101.8	-	-

Notes: * Calculated from data obtained with a continuous radon gas monitoring system (model AB-5/EL by Pylon Electronic Development).

** Defined as $(WL(Rn)/[^{222}Rn])x10^2$ where $[^{222}Rn]$ is given in pCi/L.

[1] obtained by random grab-sampling.

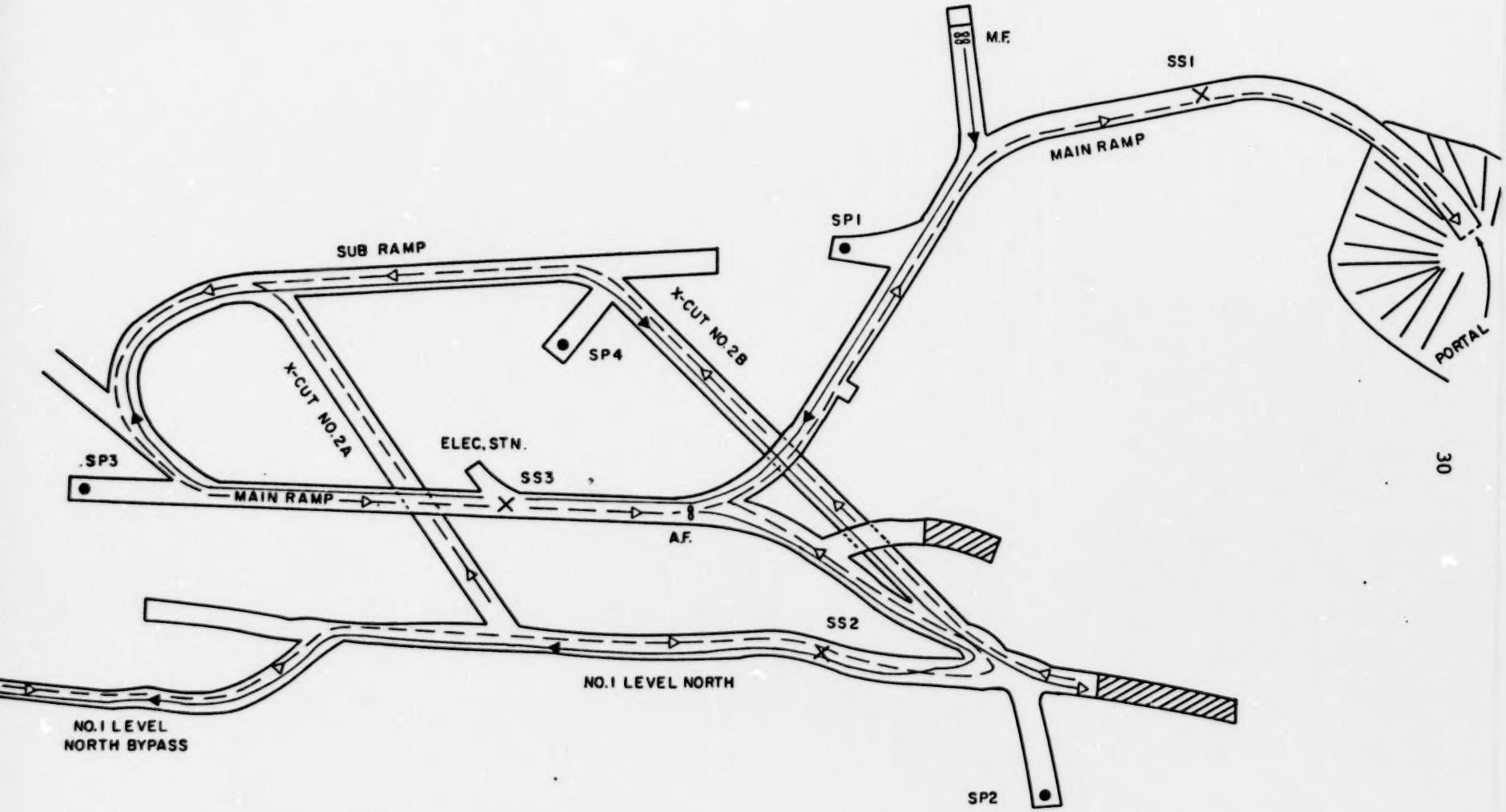

Fig. 1 - Layout of underground site where measurements were carried out. The symbols SP, MF and AF stand for sump pump, main fan, and auxiliary fan, respectively.

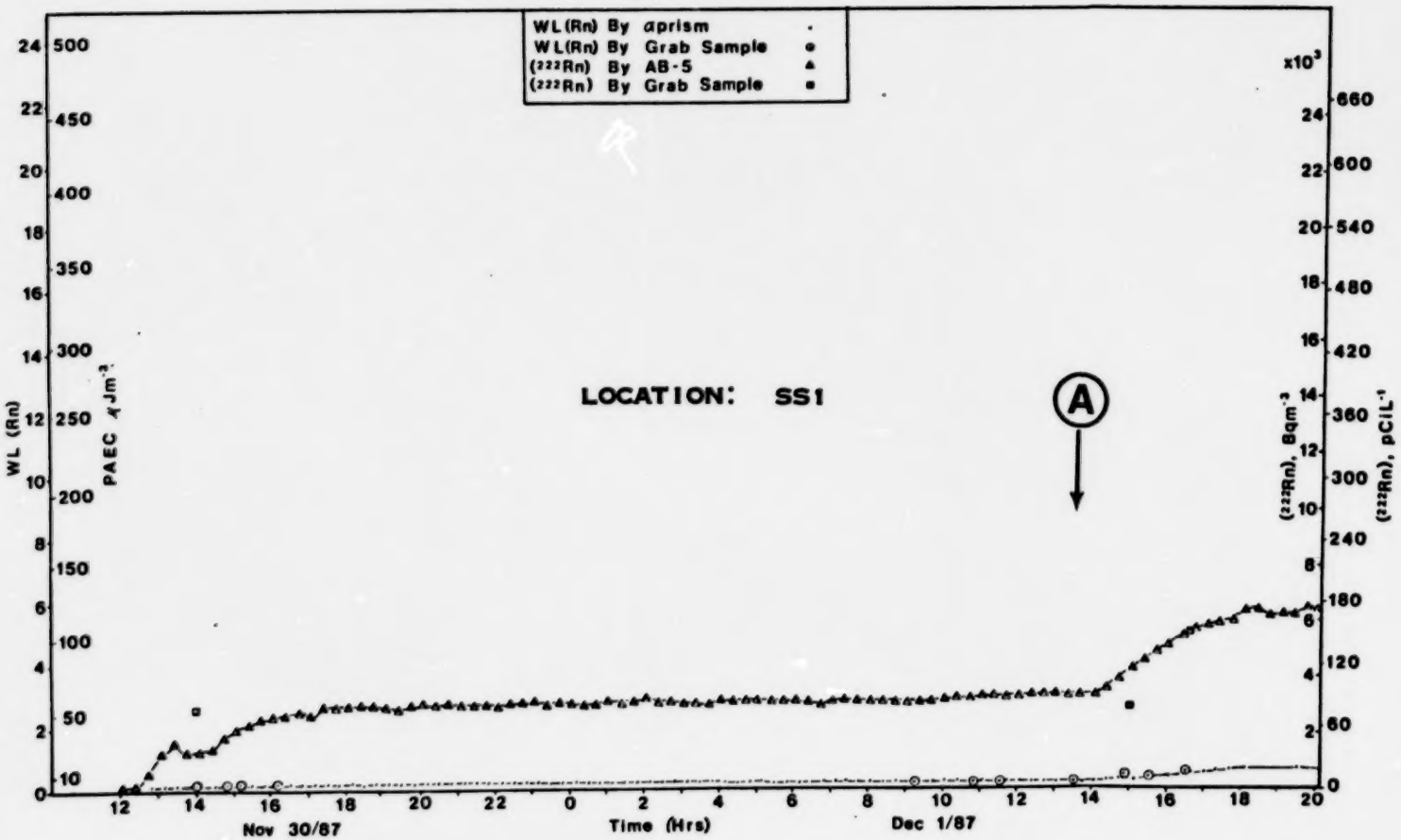

Fig. 2 - Radon gas concentration and WL(Rn) versus time at location SS1.
(See Table 1 for the meaning of A.)

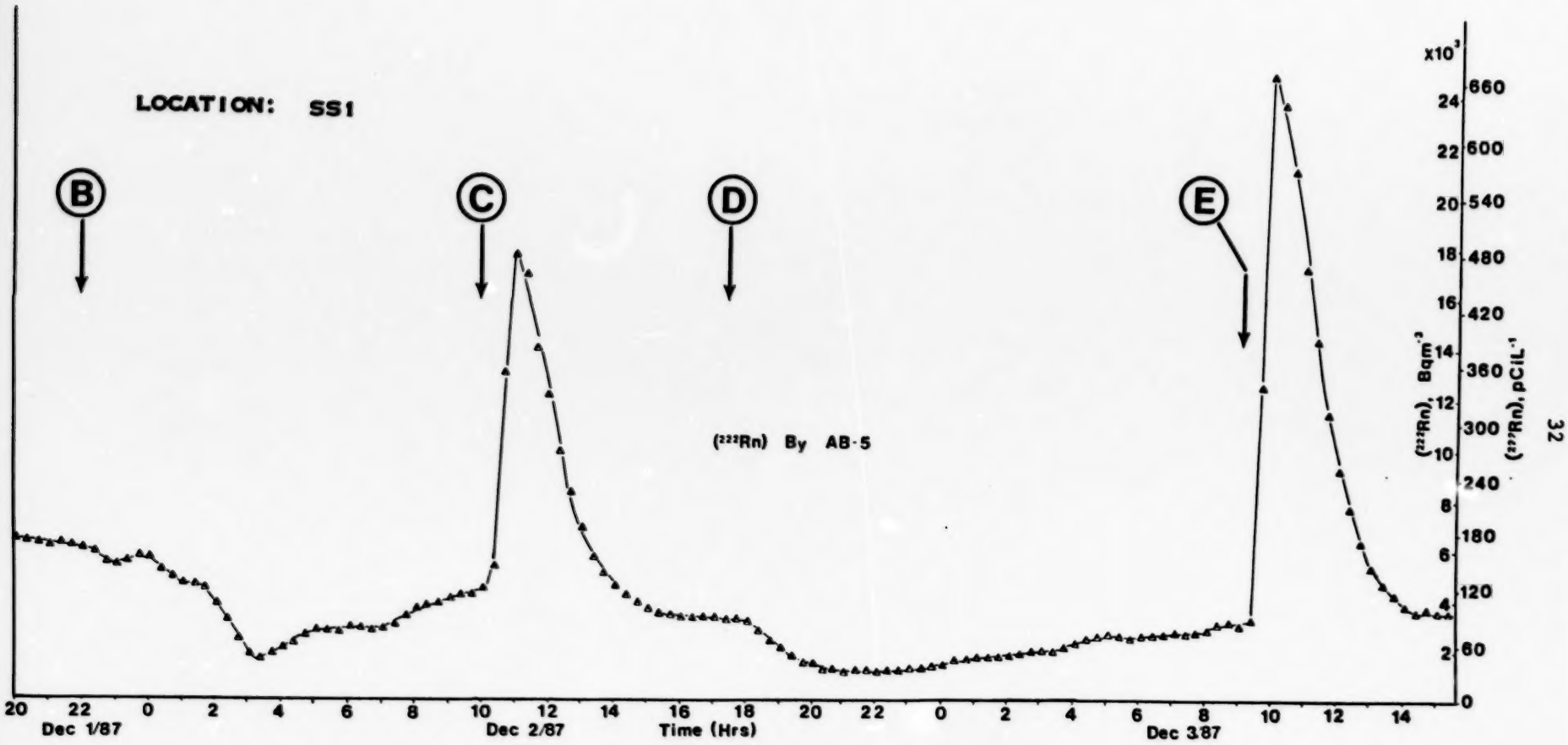

Fig. 3 - Radon gas concentration versus time at location SS1.
(See Table 1 for the meaning of the symbols A,C,D and E.)

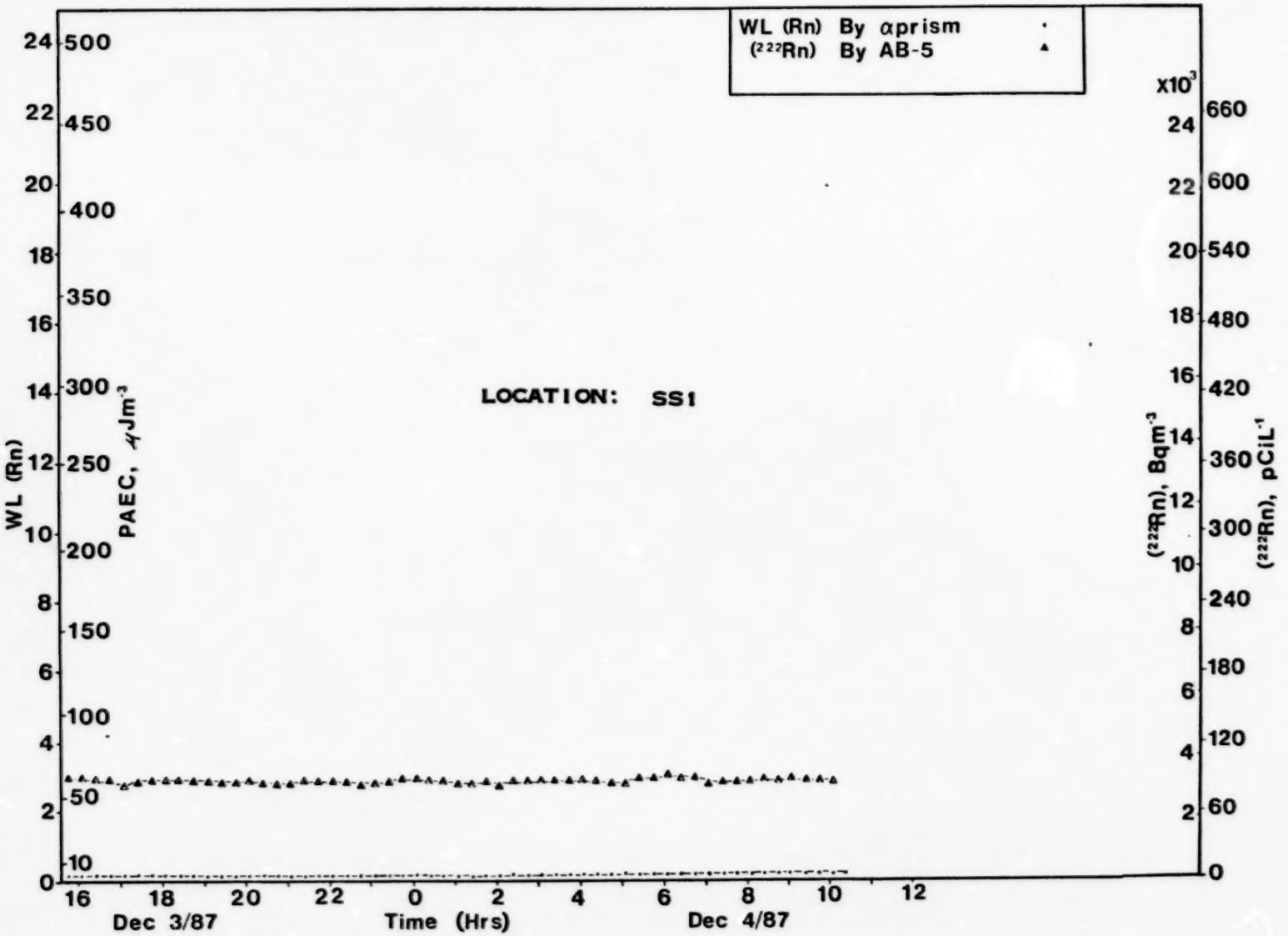

Fig. 4 - Radon gas concentration and WL(Rn) versus time at location SS1.

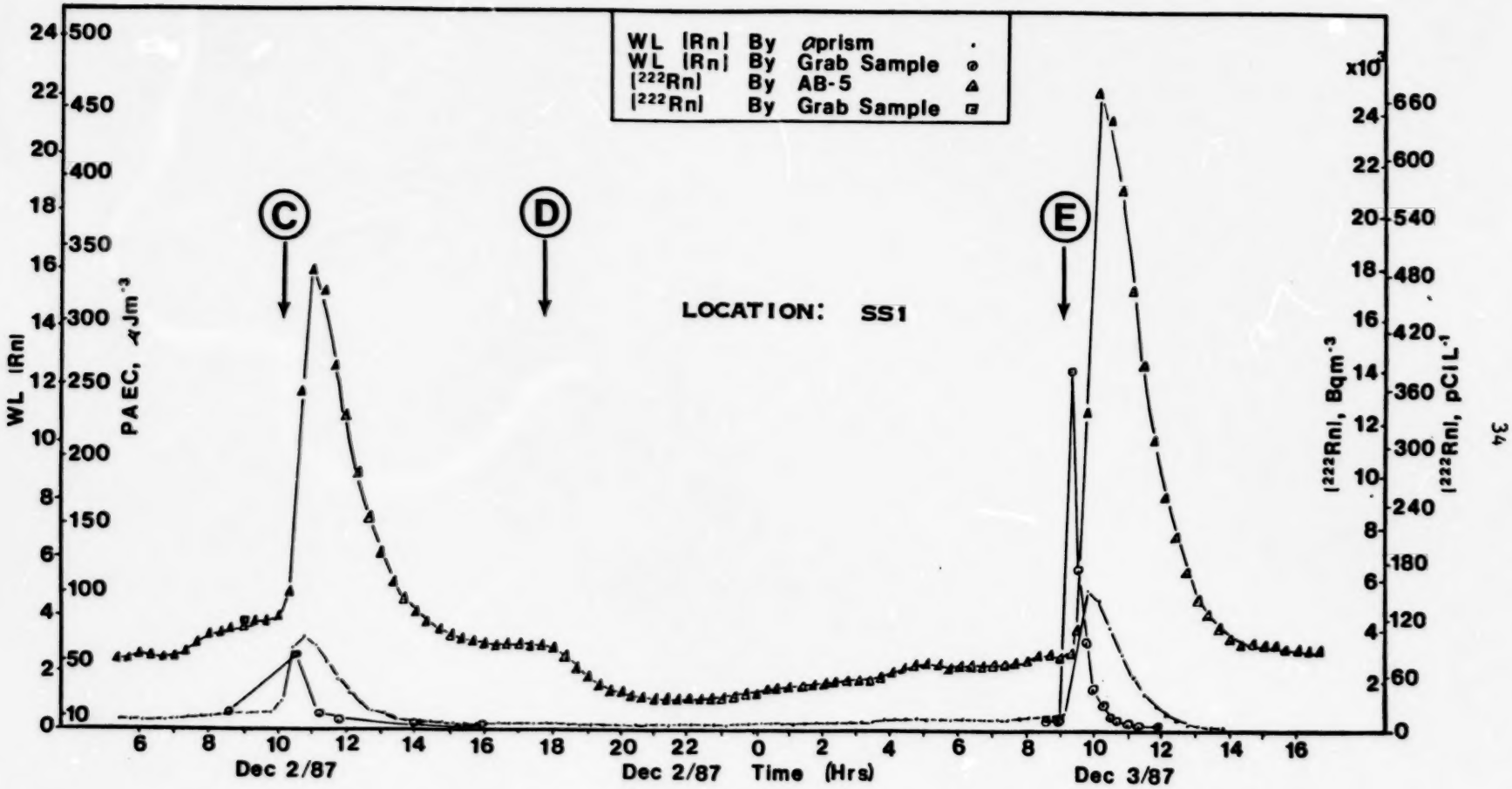

Fig. 5 - Radon gas concentration and WL(Rn) versus time at location SS1.
(See Table 1 for the meaning of the symbols C, D and E.)

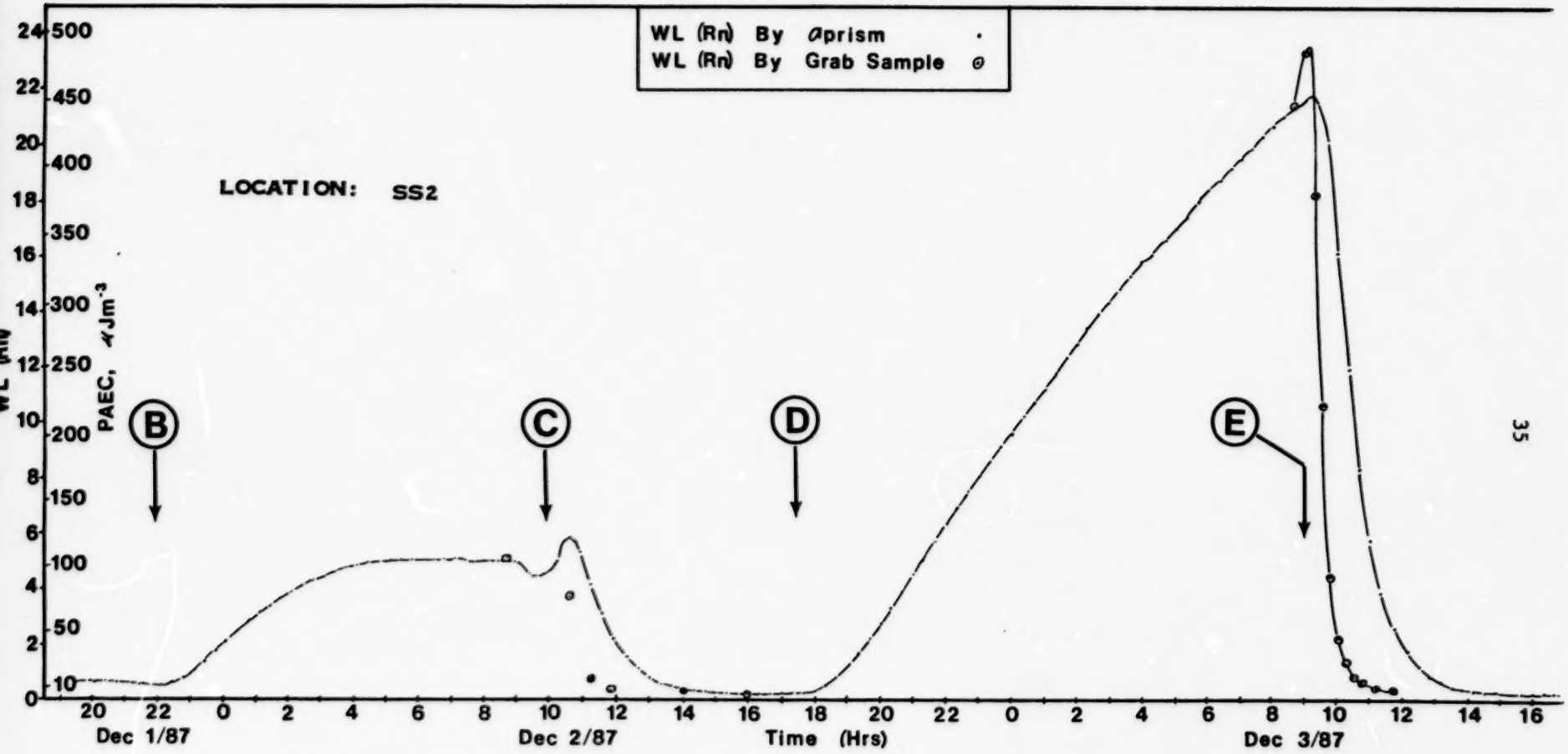

Fig. 6 - Radon progeny Working Level, WL(Rn), versus time at location SS2.
(See Table 1 for the meaning of the symbols B, C, D and E.)

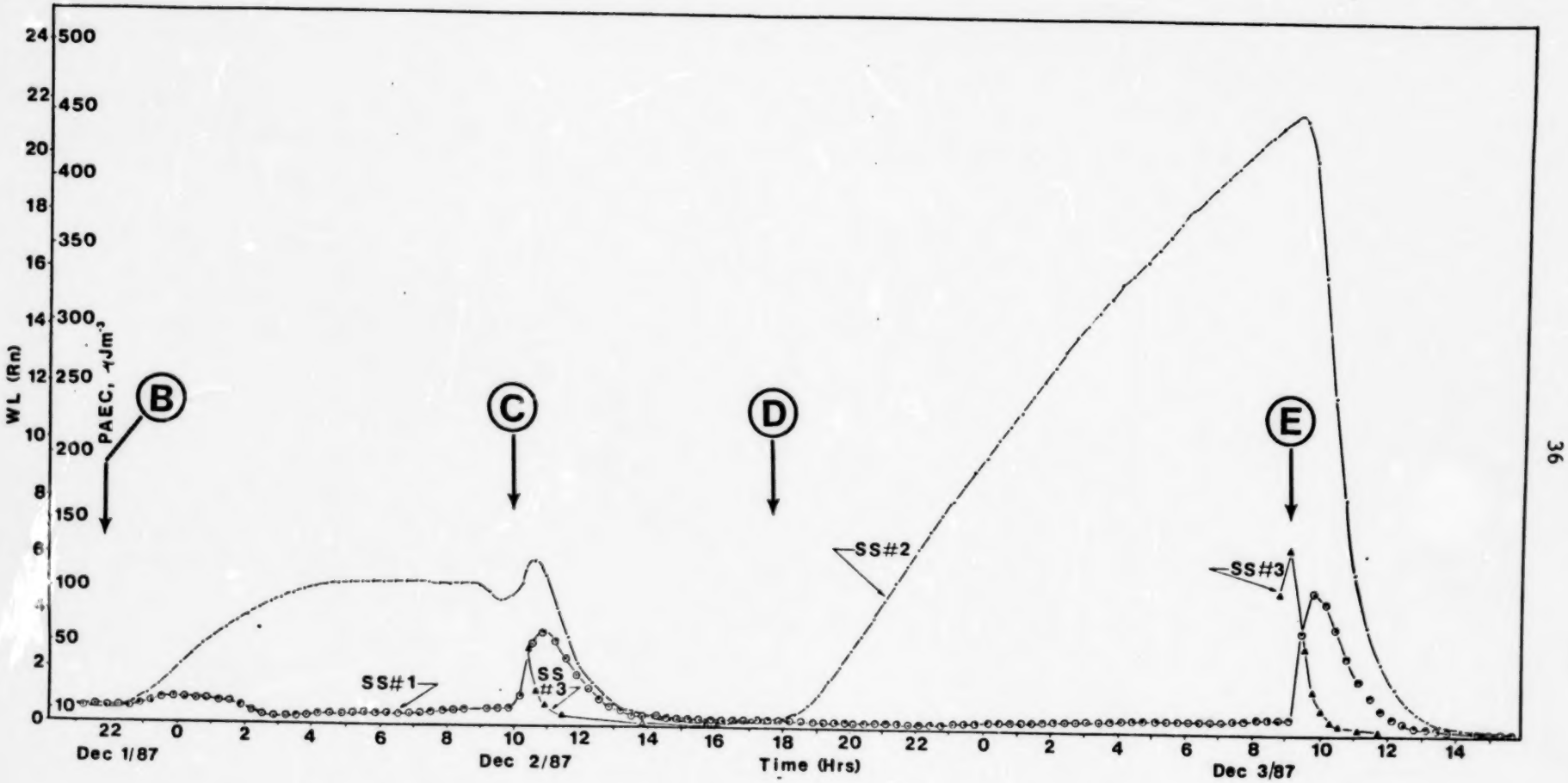

Fig. 7 - Radon progeny Working Level, WL(Rn), versus time for several locations. (See Table 1 for the meaning of the symbols, B, C, D and E.)

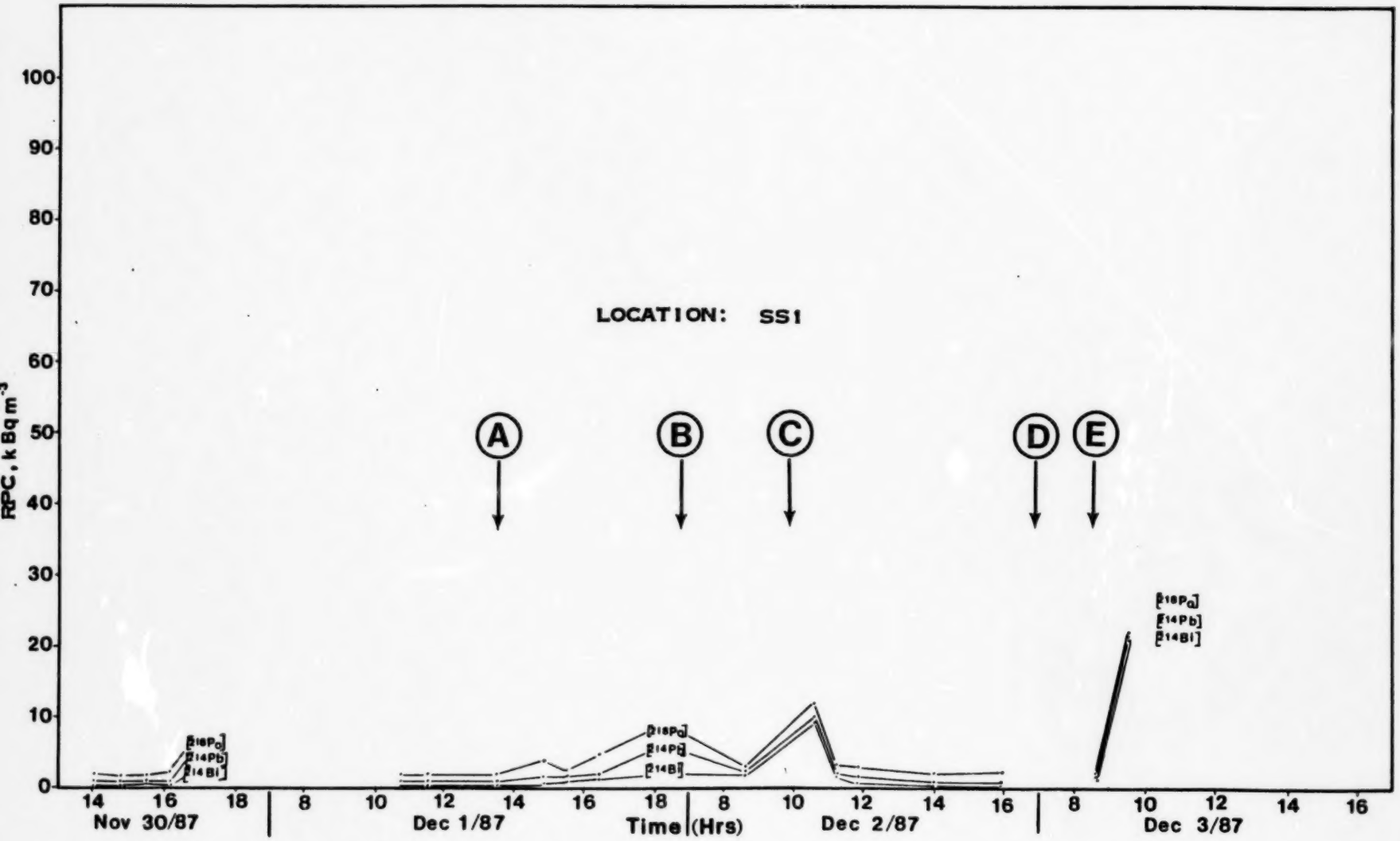

Fig. 8 - Radon progeny concentrations (RPC) versus time for location SS1.
(See Table 1 for the meaning of the symbols A, B, C, D and E.)

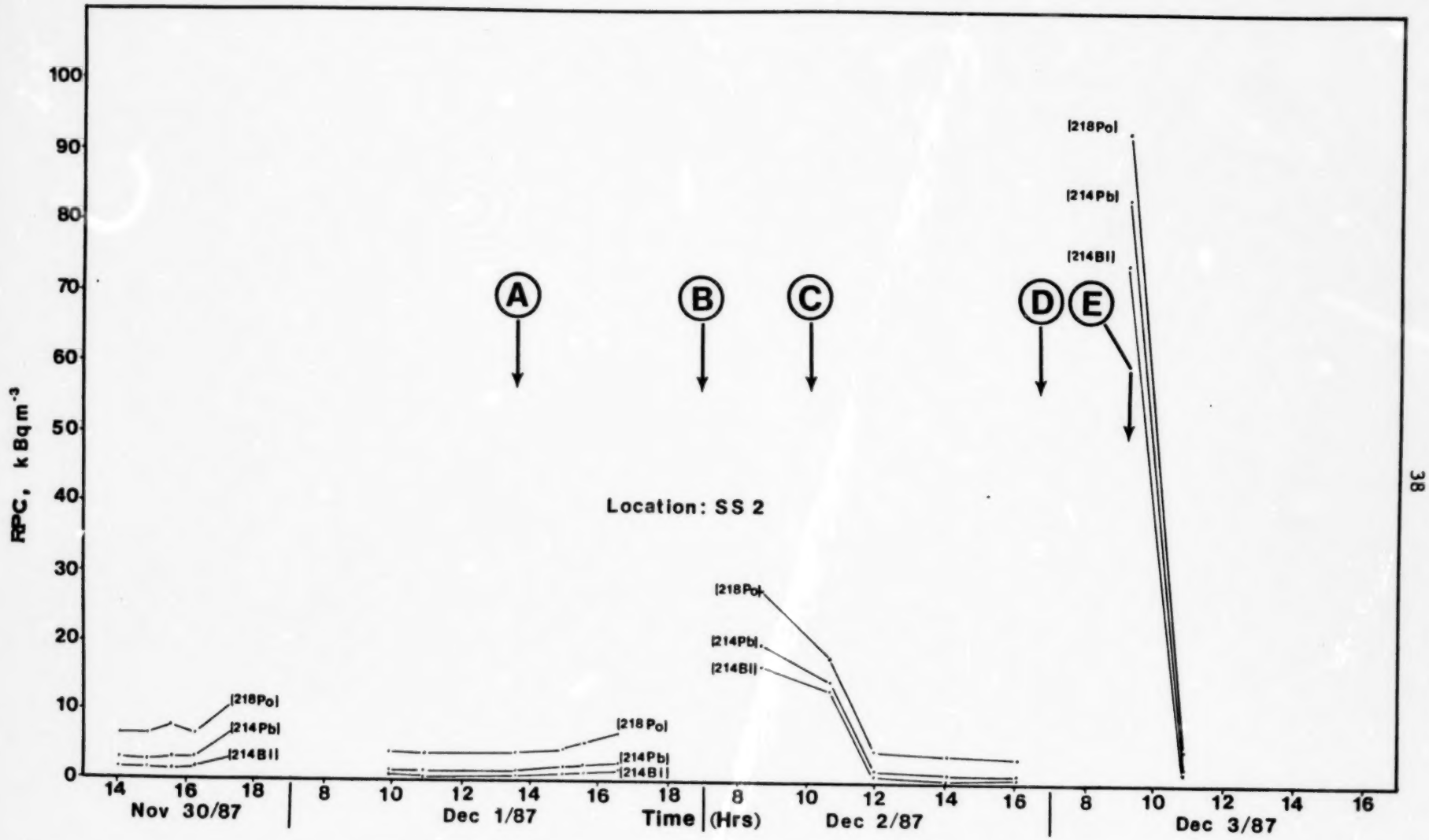

Fig. 9 - Radon progeny concentrations, RPC, versus time for location SS2.
(See Table 1 for the meaning of the symbols A, B, C, D and E.)

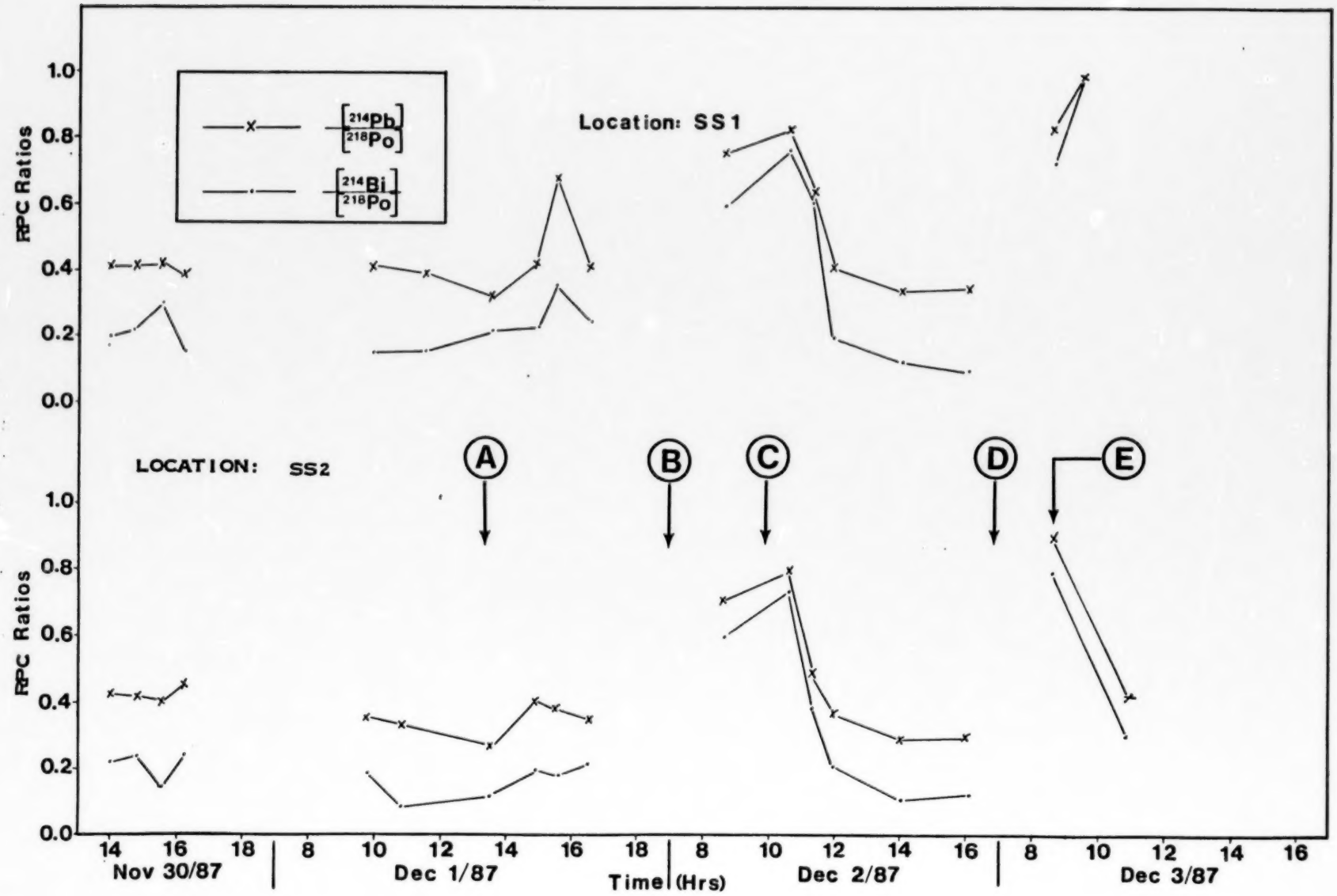

Fig. 10 - Radon progeny concentration (RPC) ratios versus time for locations SS1 and SS2. (See Table 1 for the meaning of the symbols A, B, C, D and E.)